High Sensitivity Magnetic Sensors for Biotechnology

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Outline

- Magnetic fields in biotechnology
  - Very brief introduction
  - Scanning techniques
- Magnetic fields associated with small magnetic particles (MPs)
  - Characteristics
  - Material
  - Moment
  - B fields
- Integrated magnetic field sensors
  - Spin valves
  - Magnetic tunnel junctions
  - Hall devices
- Summary

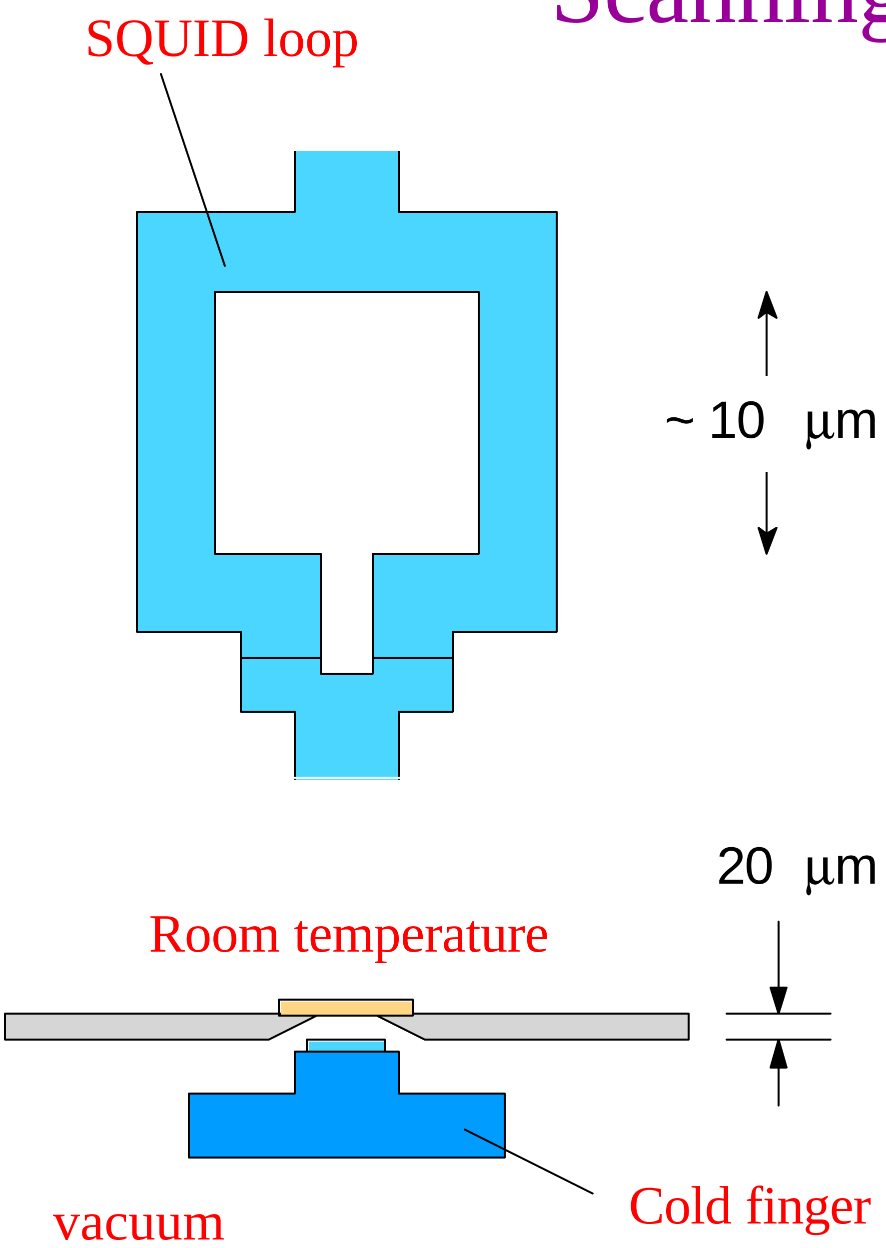
Magnetic fields in biotechnology

- A long history ...
  - E.g. Magnetoencephalography

… and a wide variety

- This talk will focus on magnetic fields that are localized on a small spatial scale
- Such fields could be associated with magnetotactic bacteria
- Or they could be generated by small magnetic particles (MPs) used to “tag” a biological or chemical agent

Scanning techniques



- Scanning (or fixed) SQUIDs
- Cryogenic sensors
- Lateral resolution limited by vertical separation
- Very high field sensitivity
- Study motion of magnetotactic bacteria (mostly ensembles, some claims of single bacterium)
- Fred Wellstood (U. Md.)
- John Clarke (UC Berkeley)
  - Biophys. J. v. 76, 3323 (99)
- Also: Magnetic force microscopes (MFM)

Detecting magnetic beads with integrated (on-chip) sensors

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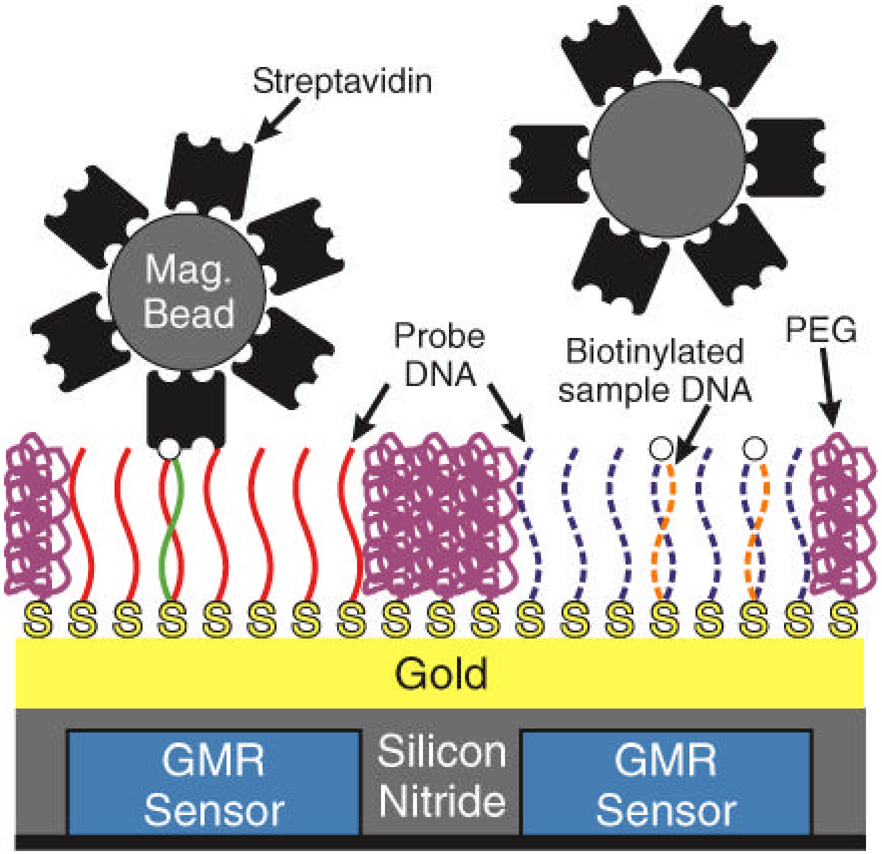

- NOT TO SCALE
- In this example, bead gets stuck to surface of chip by some chemical recognition process of interest

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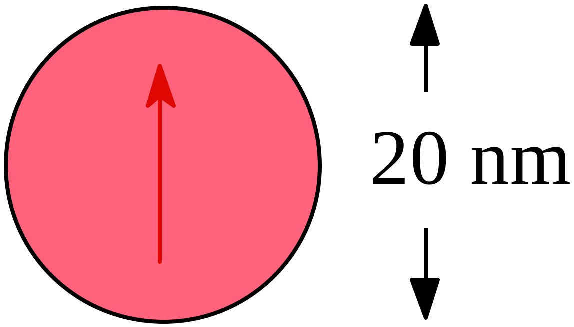
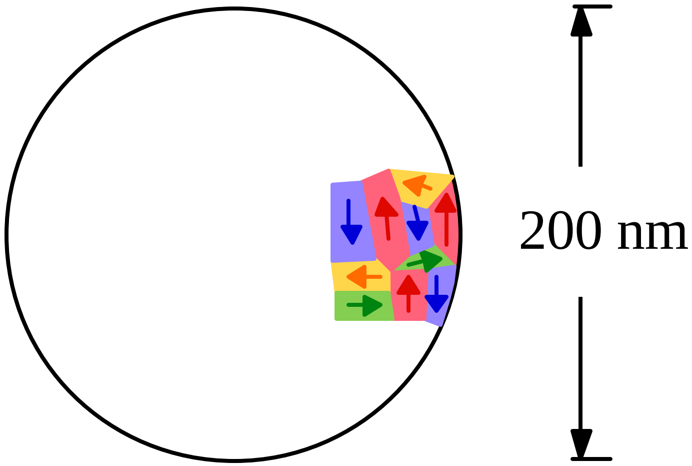
Magnetic nanoparticles (beads)





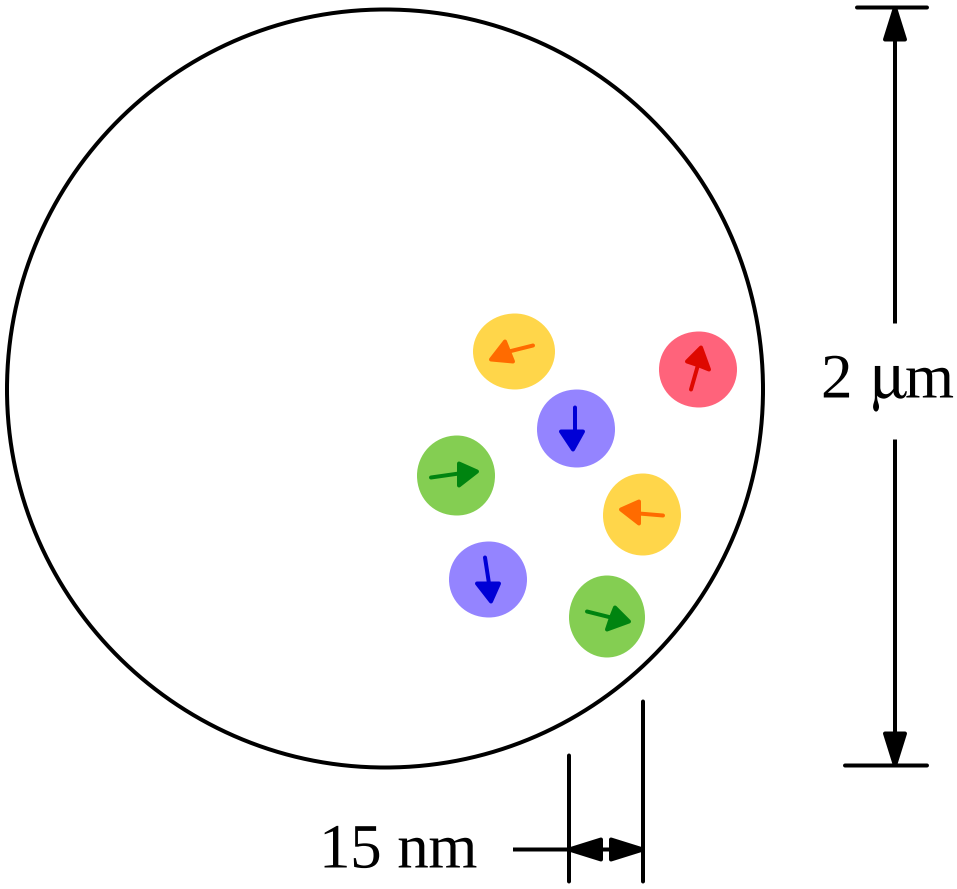
- Single domain particle (SDP), e.g. Fe, Ni, NiFe
- High remanence (always has a moment)
- Tendency to clump
- $\mathbf{m} = (4\pi/3)a^3\,\mathbf{M}$
- $\mathbf{M}$ = 1700 emu/cm^3 (Fe)
- $\mathbf{m}$ =7x10^{-15} emu (Fe, a=10 nm)

- "Soft" ferromagnetic material (Fe, Py, Ni, etc.)
- Zero remanence (NO net moment in zero field)
- Avoid clumping

Moment α applied field:

$$\mathbf{M}(H) = (3/4\pi)[(\mu-1)/\mu+2)]\mathbf{H}$$
$$= (3/4\pi)\ \mathbf{H}$$

Magnetic microparticles



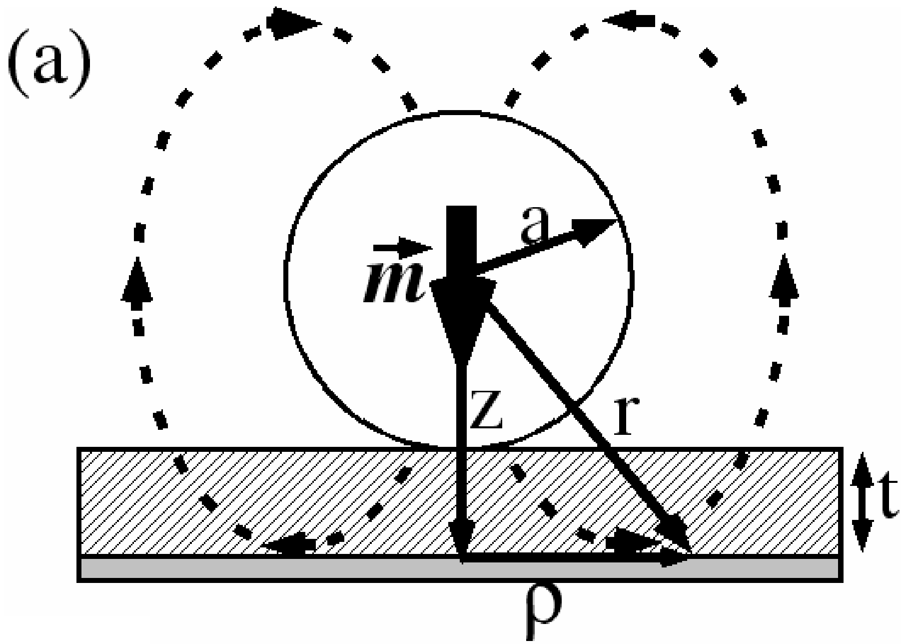
- Dynabeads (Dynal)
- Polymer matrix with embedded γ-Fe_2O_3 particles, typ. 6 to 12% vol. fraction
- Commercially available
  - Monodispersed (2.8+/-0.2 μm)
  - Functionalized, or prepared surface
- Zero remanence (NO net moment in zero field)
- Moment α applied field:

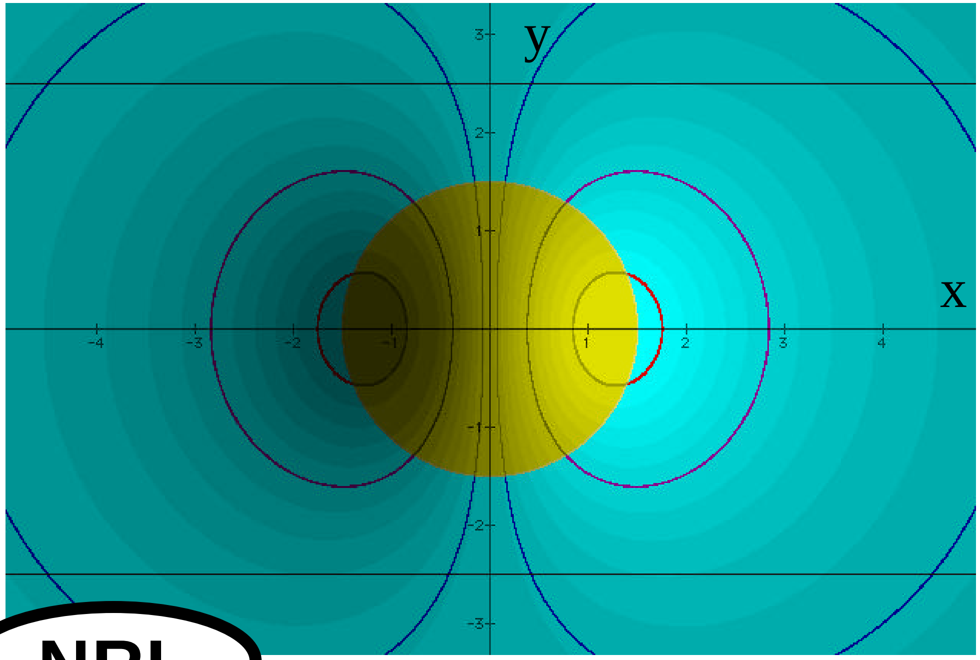
$\mathbf{M}(H) \sim (0.1)\ (3/4\pi)\mathbf{H}$

$\mathbf{M}(sat) = 10$ emu/cm^3

$\mathbf{m} = 2 \times 10^{-11}$ emu (at H=100 Oe, near sat'n; a =1.4 μm)

Magnetic dipole fields generated by MPs





In Cartesian coordinates:

$B_X = 3m(xz)/r^5$

$B_Y = 3m(yz)/r^5$

$B_Z = m(3z^2\text{-}r^2)/r^5$

$= 2m/r^3$ along z=0

For *a* = 10 nm Fe SDP:

B_Z = 12,000 Oe	t~0
B_Z = 65 Oe	t=50 nm
B_Z = 10 Oe	t=100 nm
B_Z = 1.5 Oe	t=200 nm

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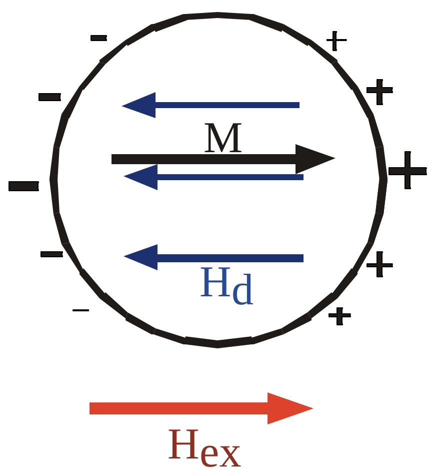
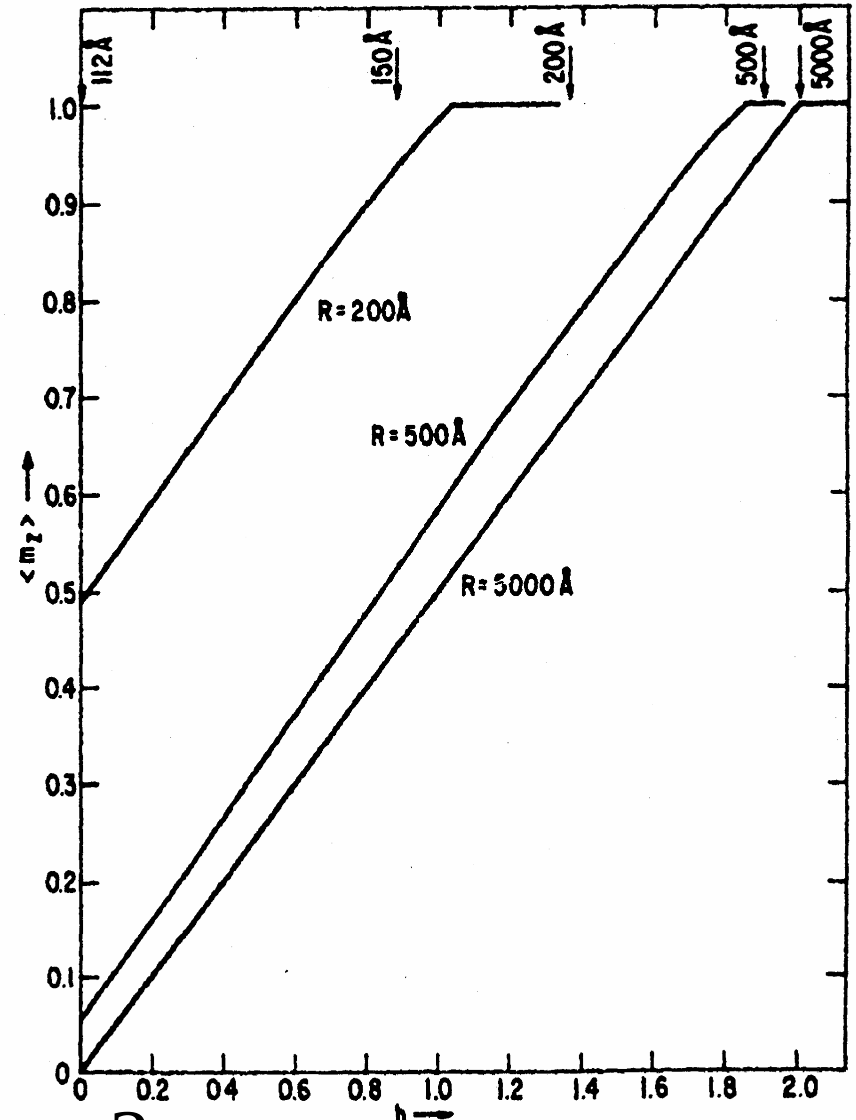
What about bigger ferromagnetic spheres

Above a =100 nm, any sphere of (low anisotropy) soft magnetic material will be an effective paramagnet





$$M_{eff} = \frac{M_{int}}{(H_A + \frac{4p}{3} M_{int})} H_{ex}$$

$$\frac{3}{4p} H_{ext}$$

A. Aharoni, J.Appl.Phys. 5, 993(1981)

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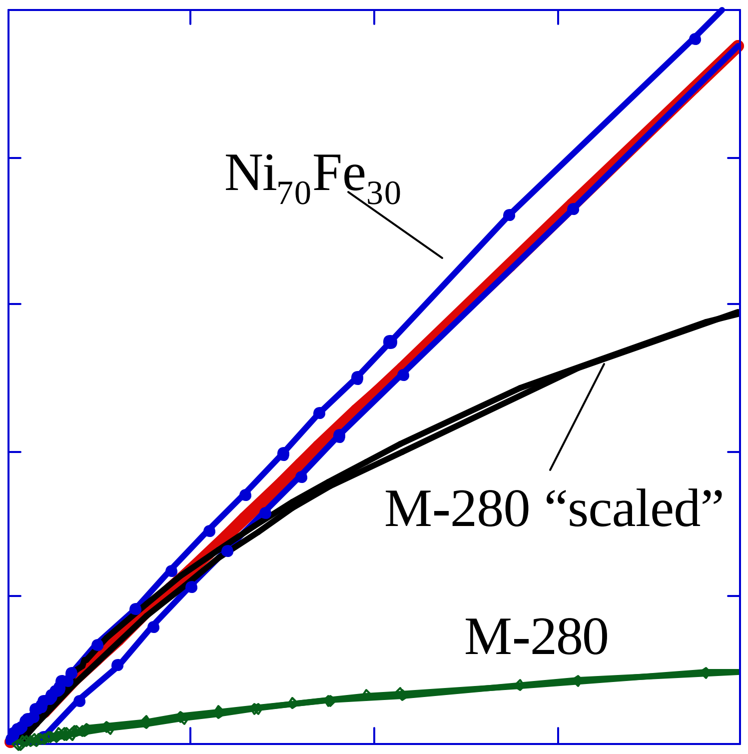
Permalloy MPs: Moments and Fields

Low Field regime



For *a* = 100 nm and H=100 Oe:

m = 1 x 10^{-13} emu

B_Z = 200 Oe t=0

B_Z = 60 Oe t=50 nm

B_Z = 25 Oe t=100 nm

B_Z = 7 Oe t=200 nm

For a Dynal bead, H = 100 Oe:

m = 6 x 10^{-11} emu

B_Z = 33 Oe t=0

B_Z = 27 Oe t=100 nm

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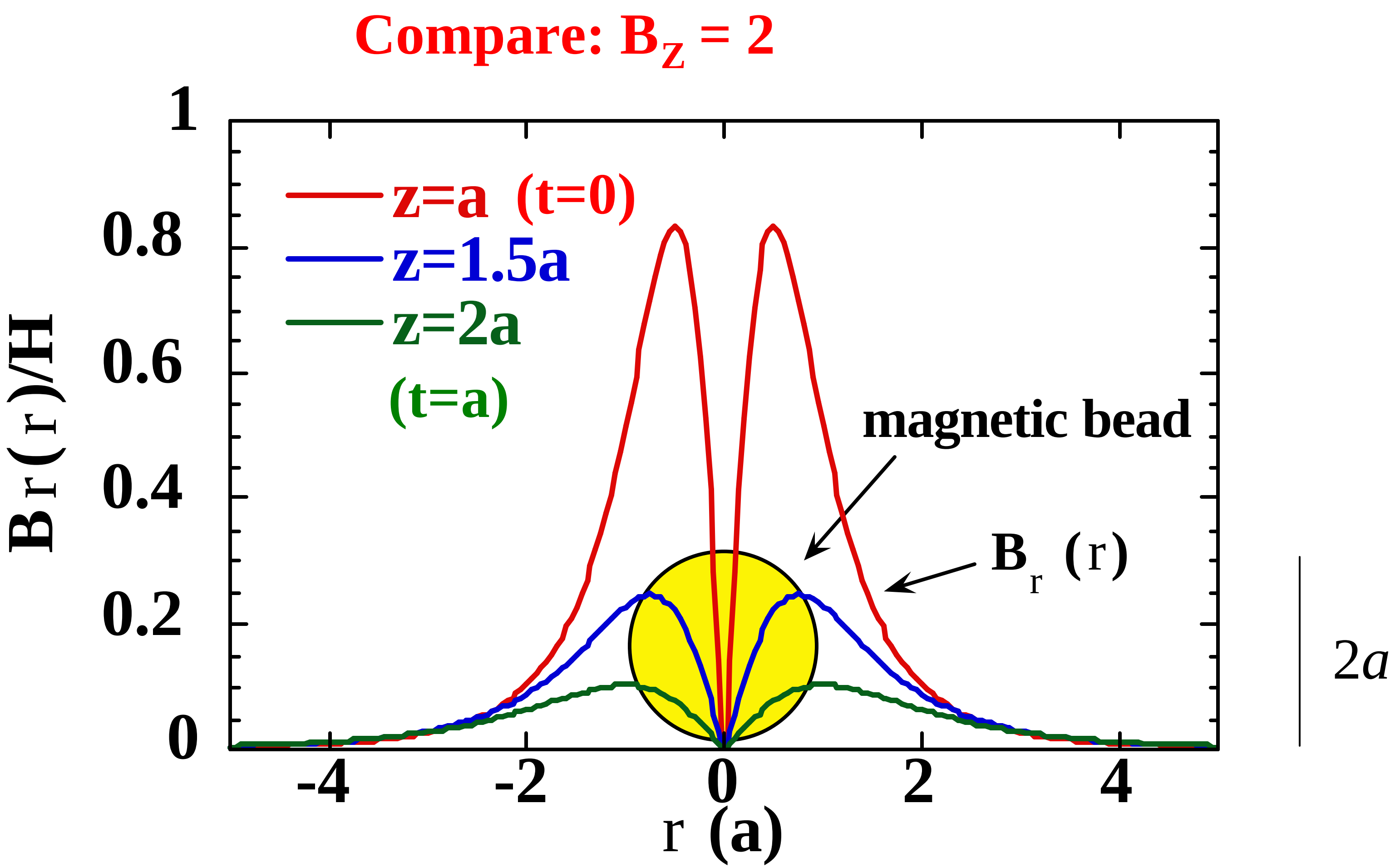
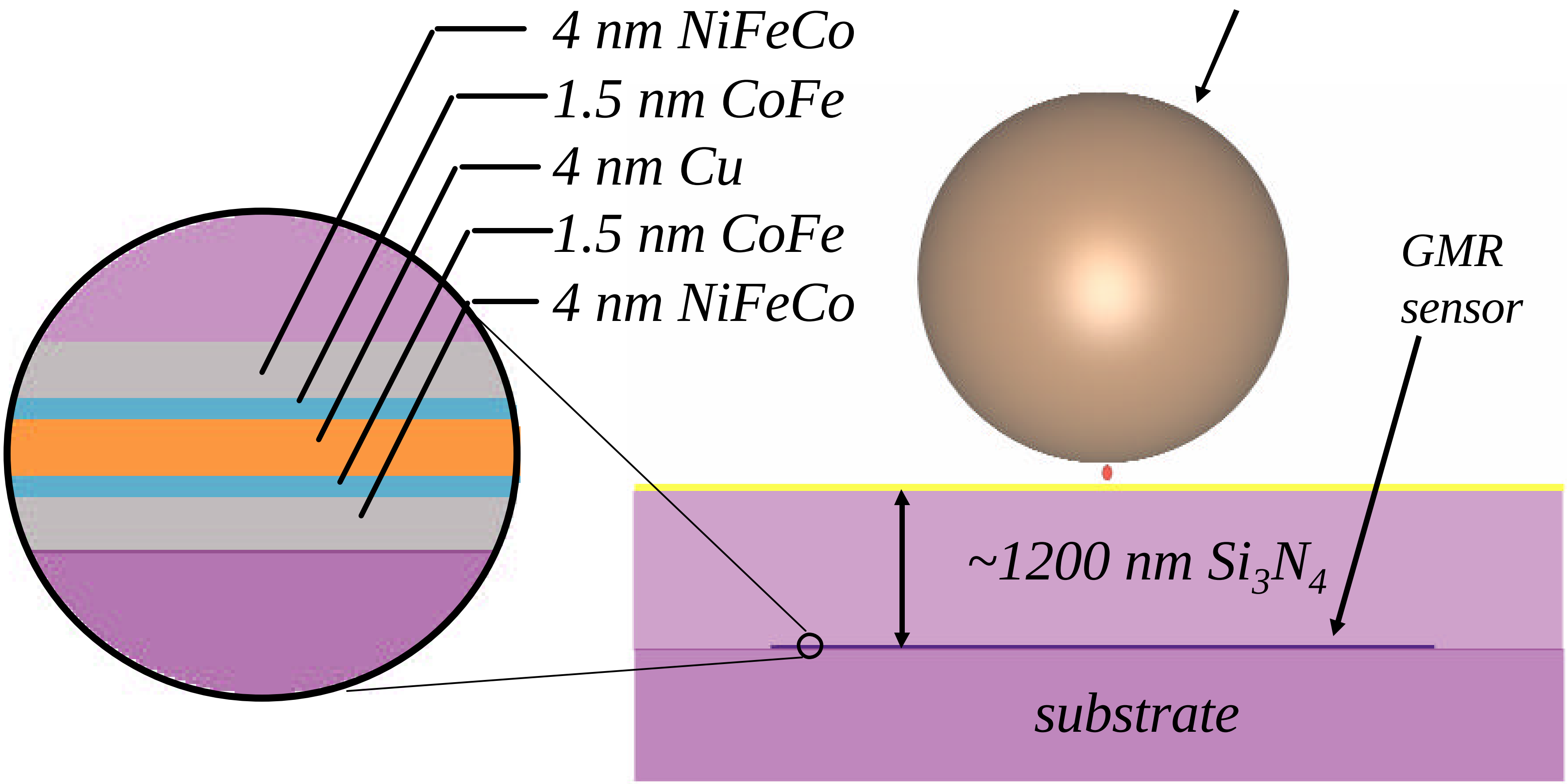
Transverse felds, Py (radial, ρ)



Typically: work with H = 100 Oe, so multiply left axis by 100 to get radial field in Oe. Detector needs to be right under MP!

Why care about radial field? Because that may be relevant to your sensor



BARC II GMR sensor structure--to scale

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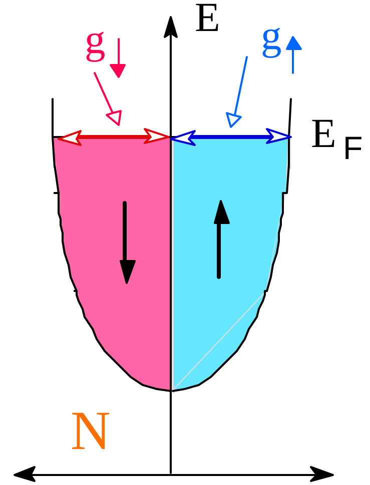
Transport properties of metals

Nonmagnetic metals:
e.g. Cu, Au, Ag, Al
R is a few μΩ-cm



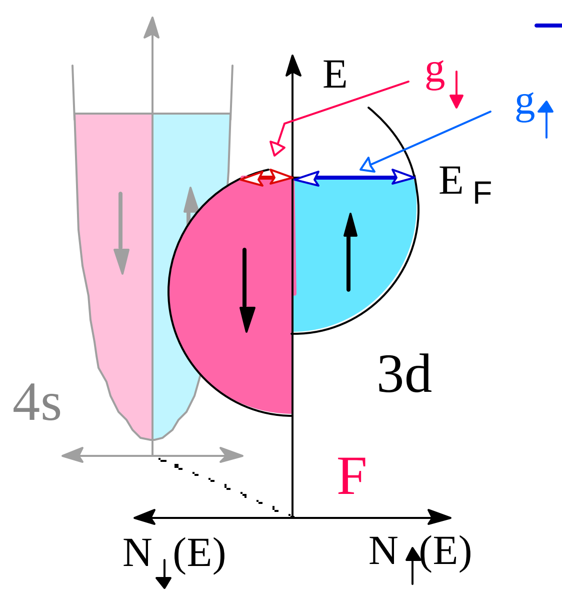
$g \;\alpha N(E$ `

$g_\downarrow$ and $g_\uparrow$
don't mix
(orthogonal)

$$g = g_\downarrow + g_\uparrow$$

$$g_\downarrow = g_\uparrow$$

Transition
metal Ferro-
magnets, e.g
Ni, Fe, Co, NiFe
R is 10s μΩ-cm



$$g_\downarrow \neq g_\uparrow$$

$$P = \frac{J_\uparrow - J_\downarrow}{J_\uparrow + J_\downarrow}$$

$$= \frac{g_\uparrow - g_\downarrow}{g_\uparrow + g_\downarrow}$$

Tunnel MagnetoResistance (TMR) - (aka MTJ)

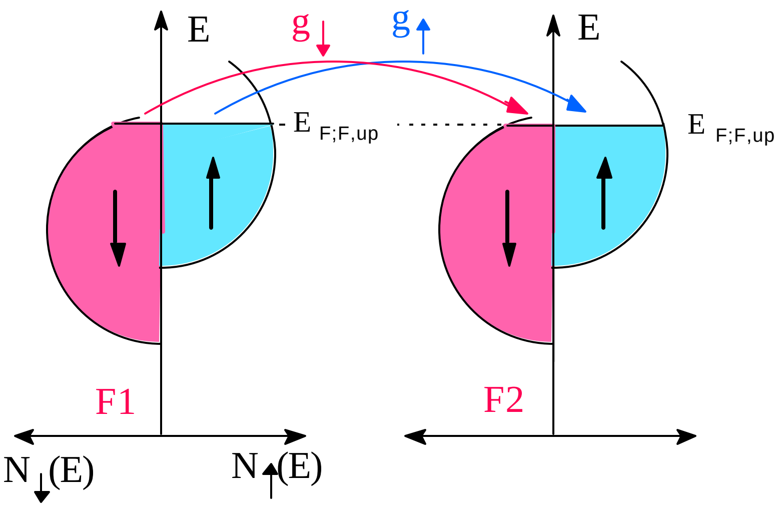
$g \propto N(E)_F$

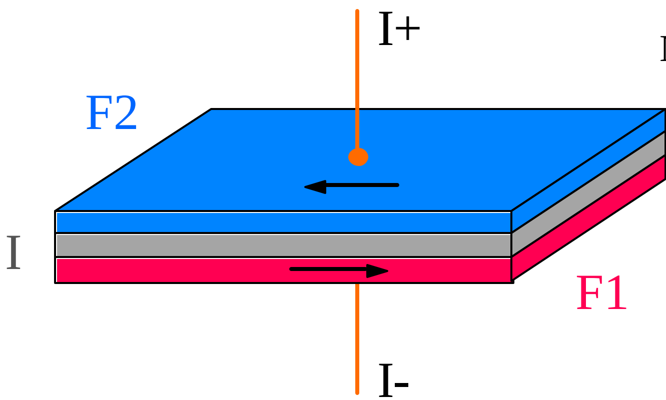
F1 and F2 parallel :

$g_{\uparrow} > g_{\downarrow}$

$g_{\uparrow}$ dominates

Low R state

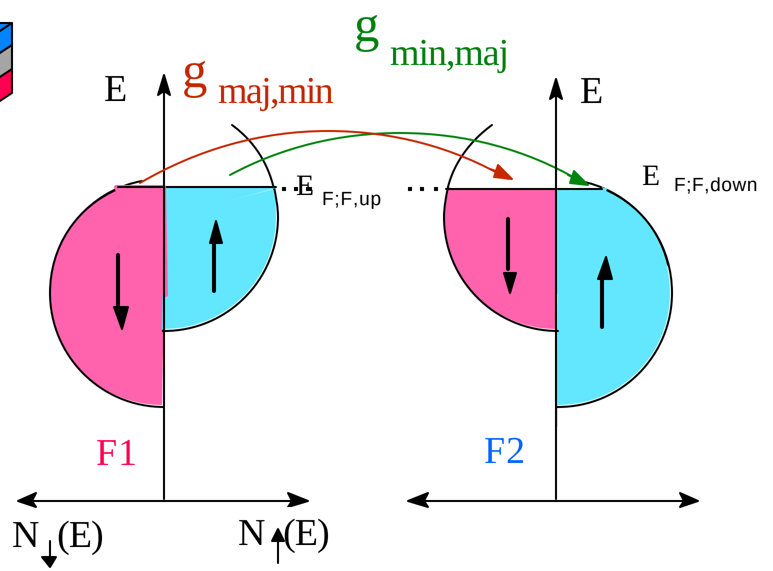




F1 and F2 antiparallel :

$g_{min,maj} = g_{maj,min} < g_{\uparrow}$

High R state



Juliere (1975) ; Moodera *et al* (1995)

Assumption: NO spin flip during tunneling

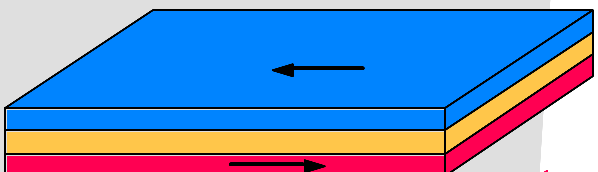
Magnetoresistance - spin valve

$g \;\alpha N(E_F)$

$g_{\uparrow}$ $g_{\downarrow}$

$g_{\uparrow}$

Low R state



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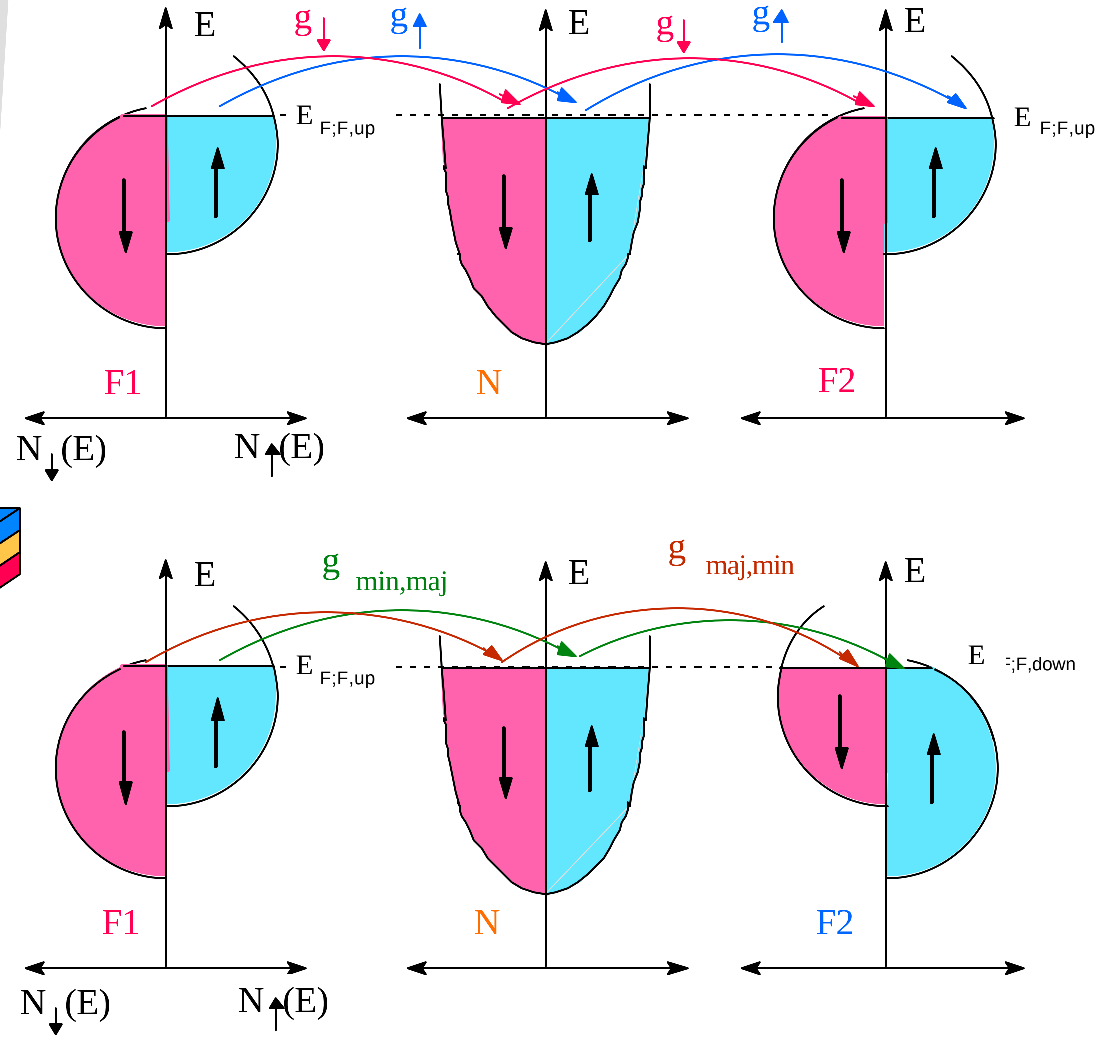
:

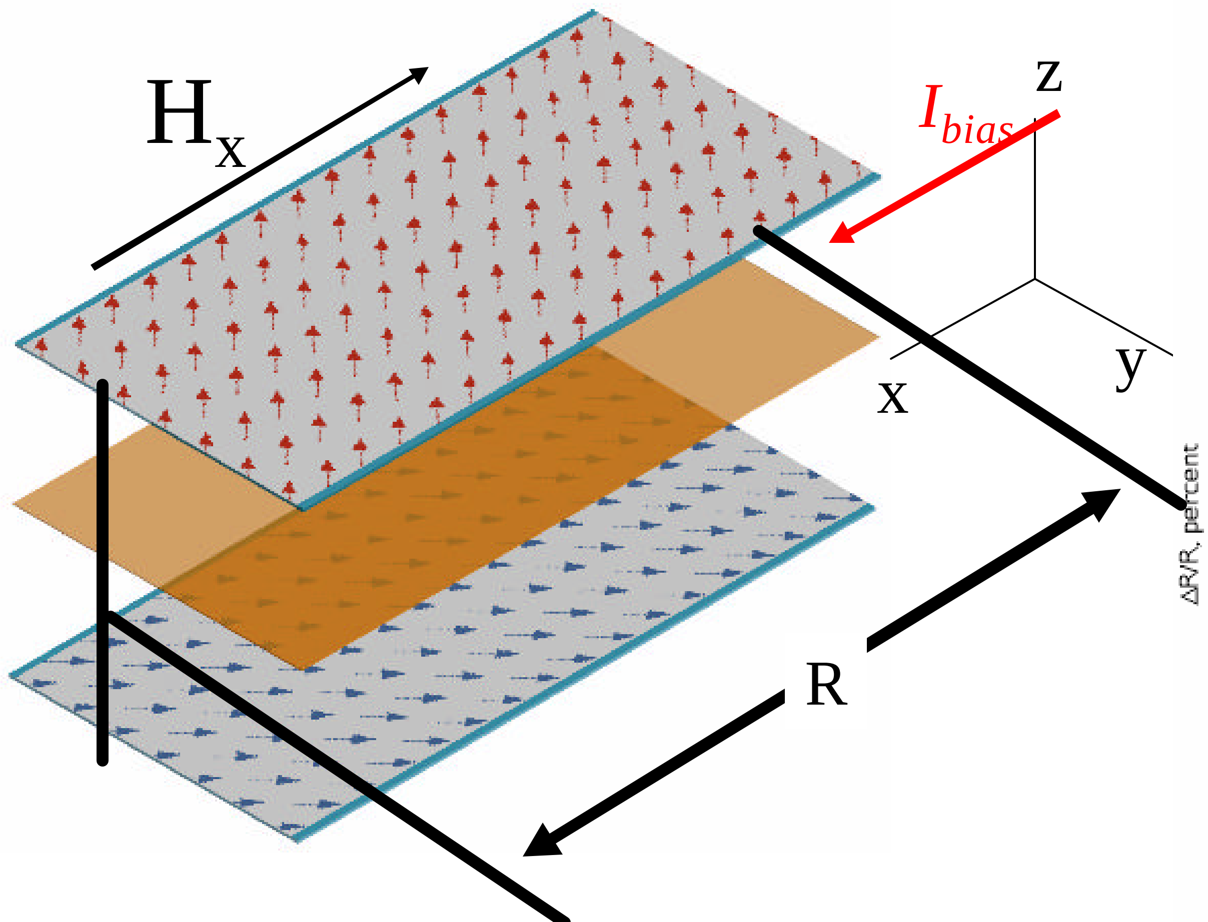
$g_{min,maj}$ $g_{maj,min}$ < $g_{\uparrow}$

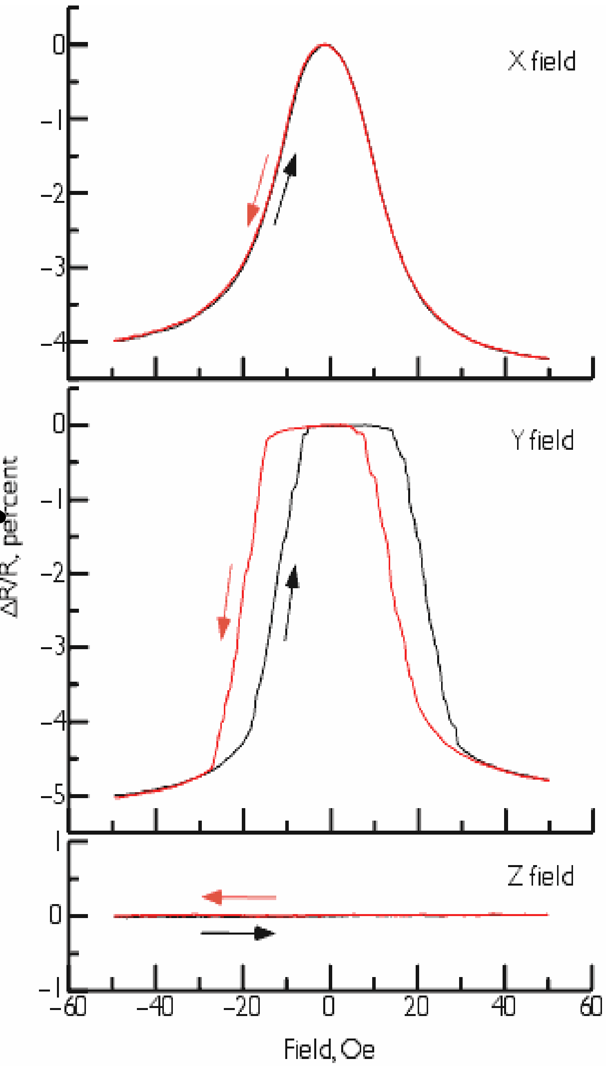
High R state



Grunberg PRB (89), Fe/Cr spin valve MR=1.5%
Baibich et al., PRL (88), Fe/Cr multilayer

GMR Magnetic Field Sensor Scissors Mode: Uniaxial sensitivity





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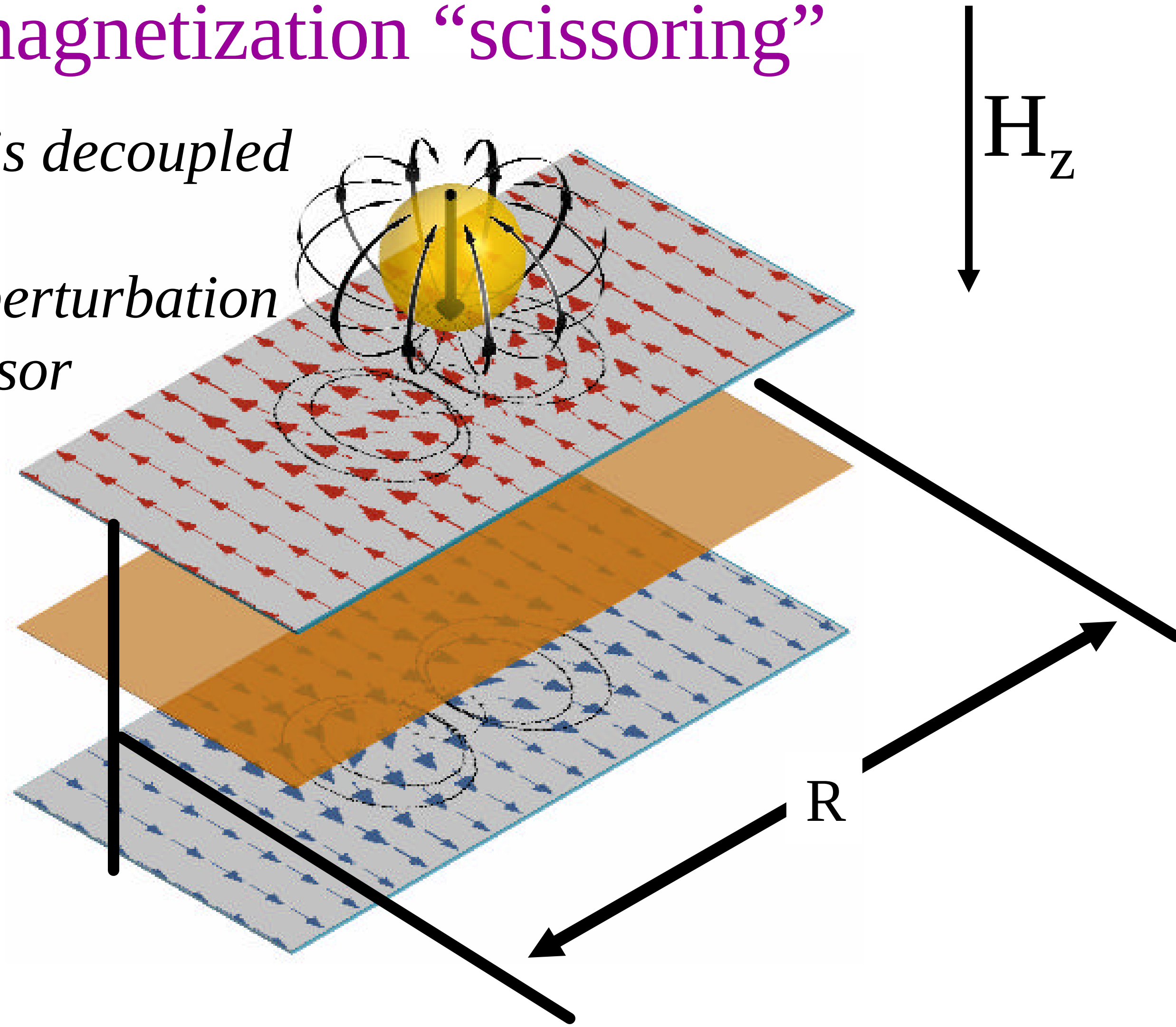
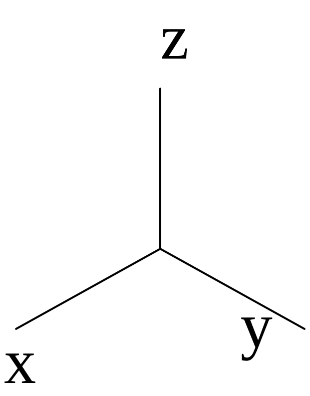
Localized magnetization “scissoring”

- *Absent a bead, sensor is decoupled from applied H_z*
- *Bead induces a small perturbation to total resistance of sensor*
- *DR ~ number of beads*

Dynamic range x100
(sense 10 to 1000 beads)





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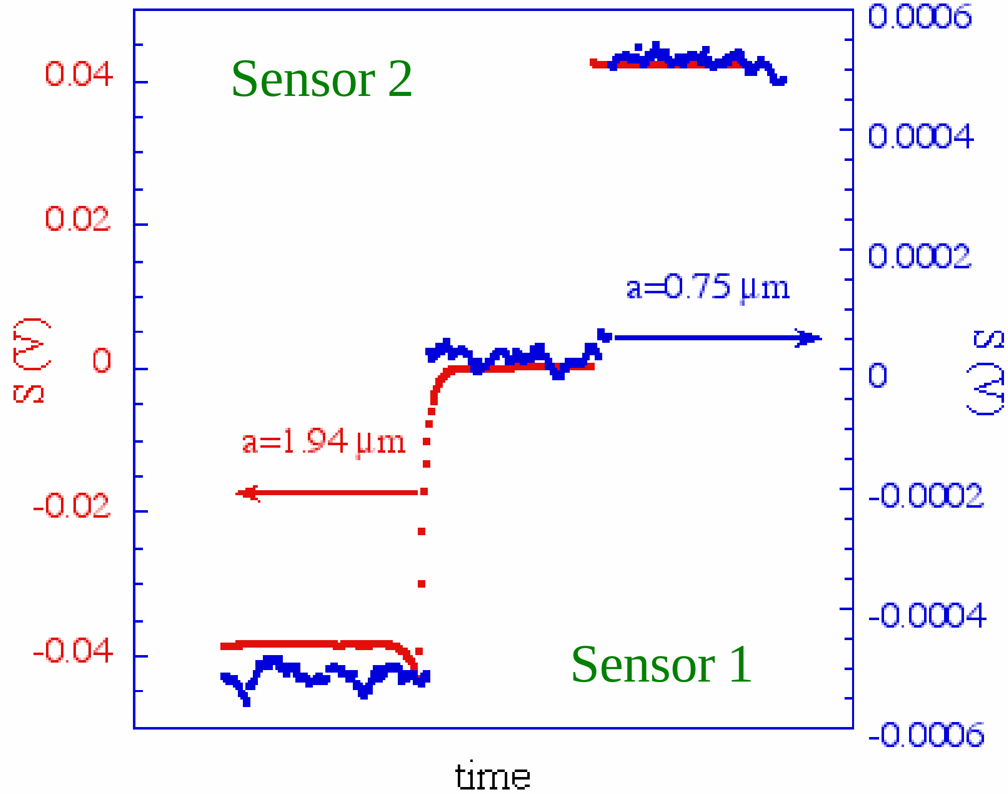
Example of BARC detection



- O.75 and 2.0 µm Py beads
- Sensor 2 not shown (bridge geometry)
- Move beads between Sensors 1 and 2
- Bigger signal for bigger beads!

1. *Biosensors & Bioelectronics* ***13***, *731-739 (1998)*
2. *Biosensors & Bioelectronics* ***14***, *805-739 (2000)*
3. *J.Mag.Mag.Mat.* ***225***, *138-144 (2001)*

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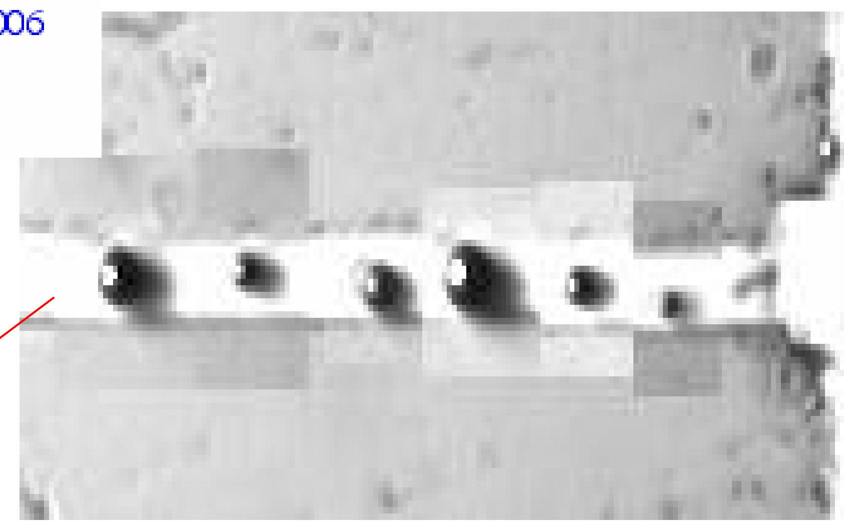
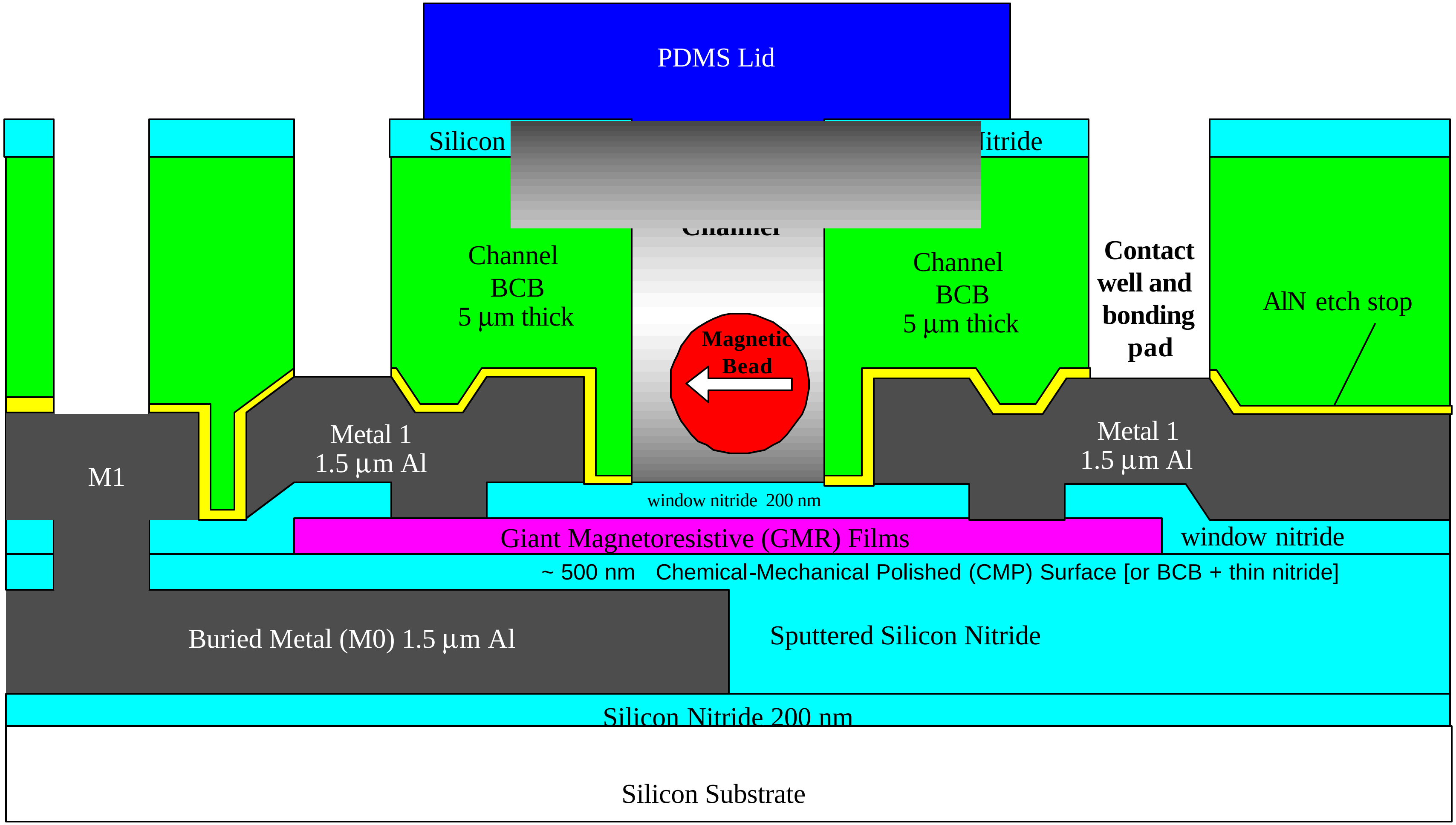
Sensor 1



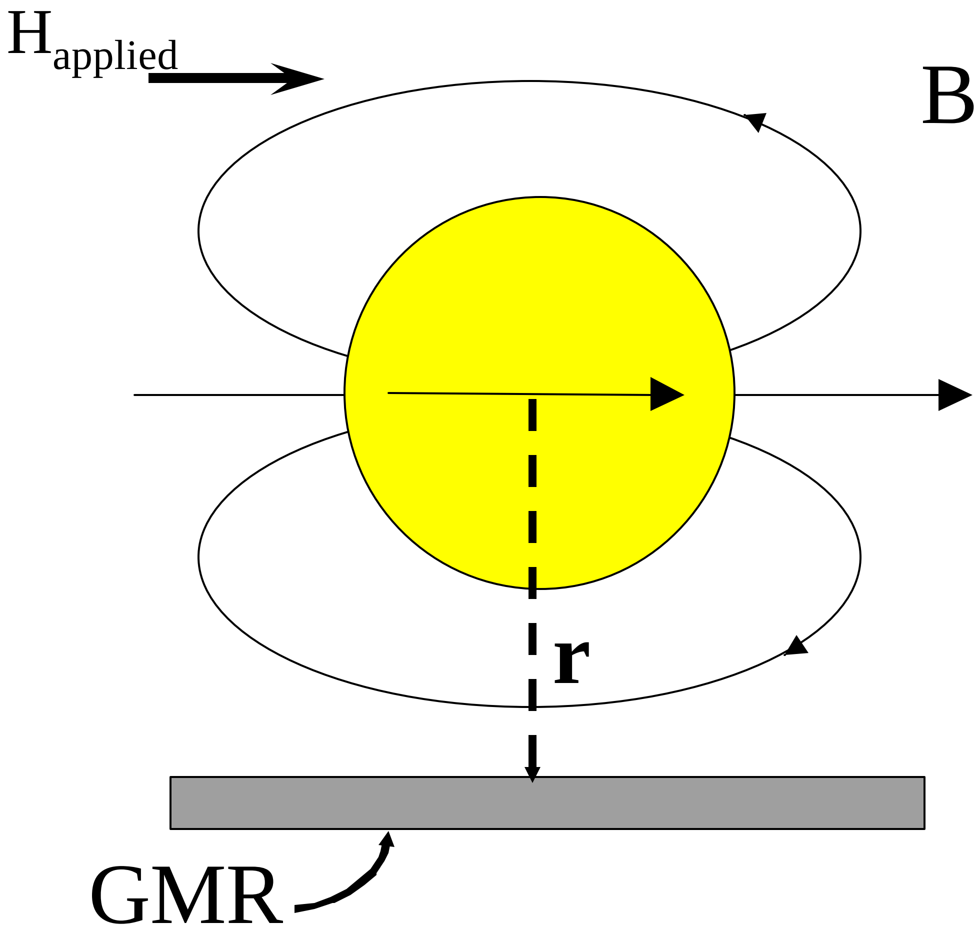
NVE

GMR / Fluidics Process Cross Section
Integration of fluidics and sensing



NVE

Stray Fields from Magnetic Beads



Bead Field ~ $1/\mathbf{r}^3$

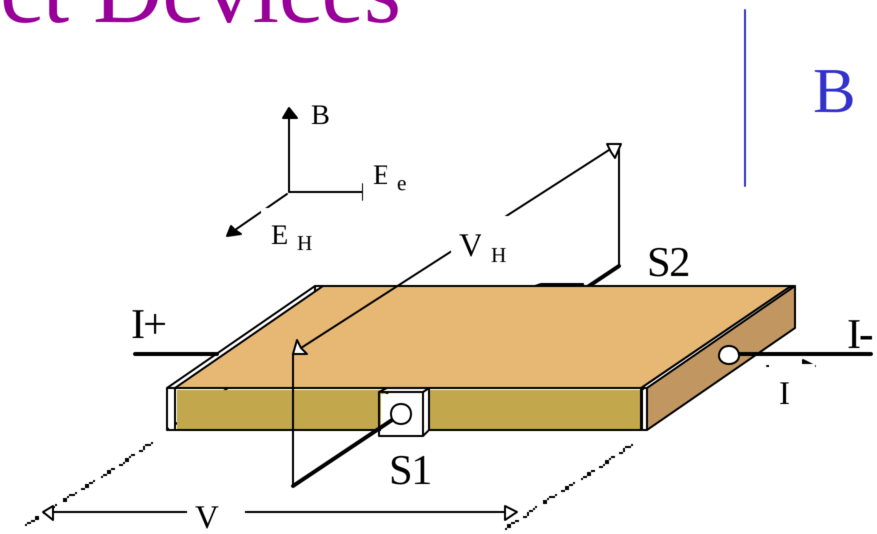
At 1 bead radius away, the stray field ~ cancels the applied field

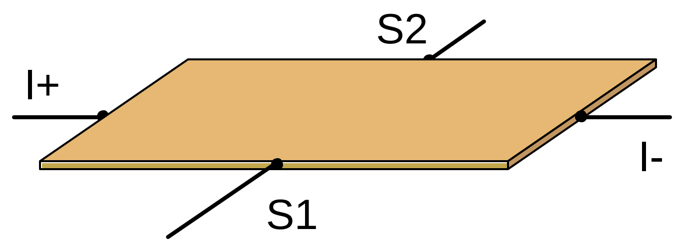
MR sensors (magnetic tunnel junctions and spin valves)

- Sensor technology (individual sensors) mature
  - Concern about scaling and micromagnetism
- Memory array technology (arrays of many sensors) still in "research and development"
- Many players
  - Mark Tondra (NVE)
  - Jagadeesh Moodera (MIT, Bitter Magnet Lab)
  - Gang Xiao (Brown)
  - Shan Wang (Stanford)

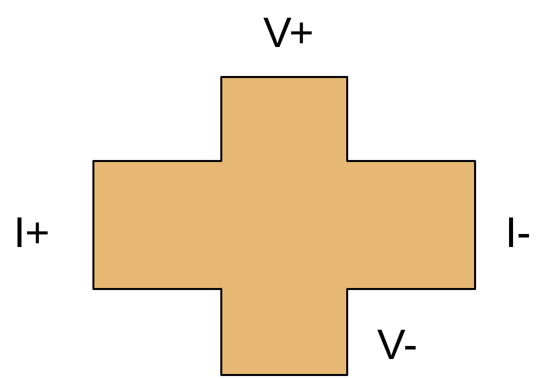
Hall Effect Devices

- Sensitive to perpendicular fields, B_Z
- Classical Lorentz force, **v** x **B**
- $(V_H / I) = (R_H / t)\, B_Z$
- $R_H \propto 1/n$ (n=density of carriers)
- Sensitivity for high mobility heterostructures (InAs): 0.5 Ω/Oe
- Good scaling



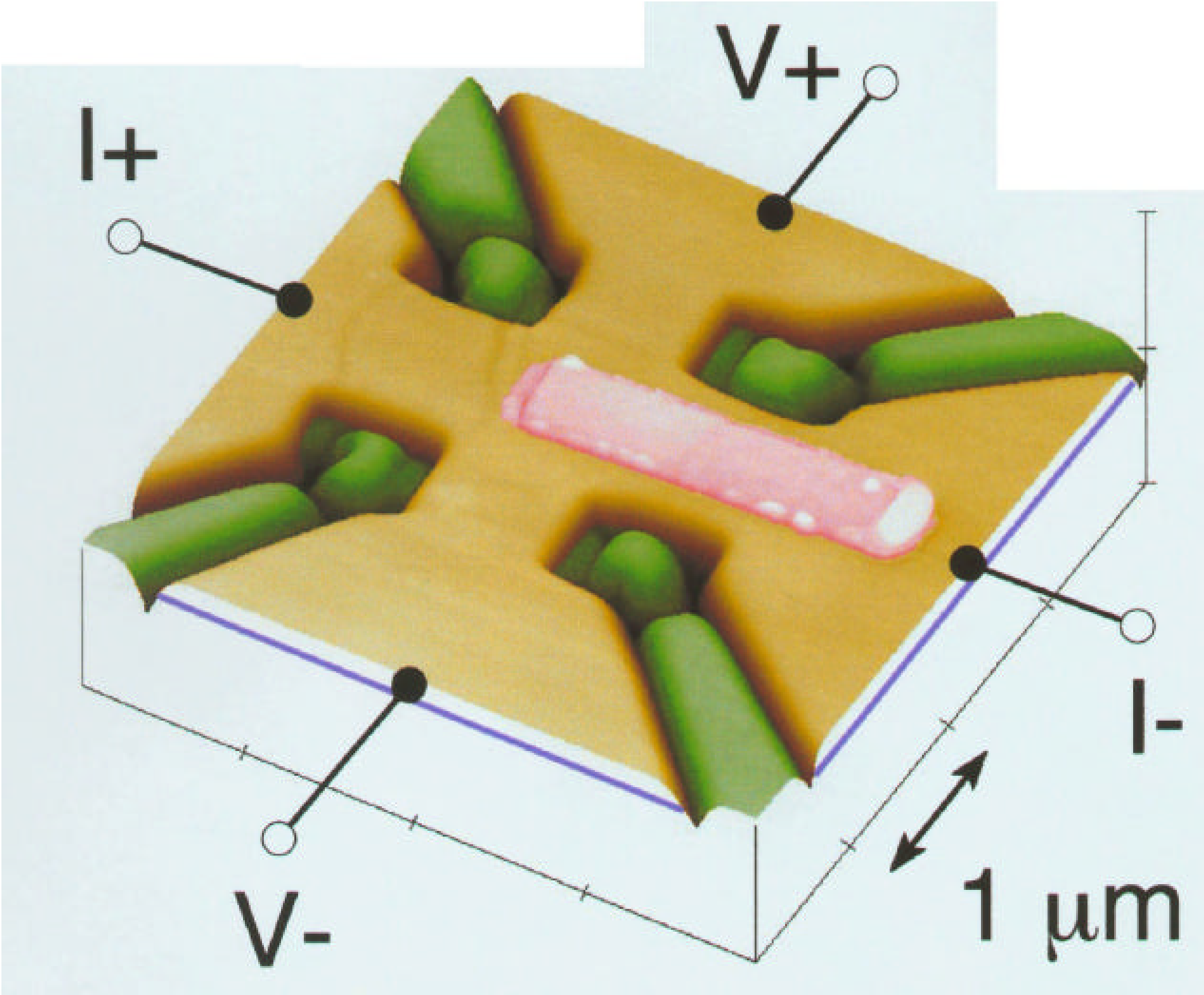


TOP VIEW
Schematic,
Patterned
device



Hall cross fabricated by FIB

- Example of Hall device developed for nonvolatile memory
- False colored AFM image
- Hall plate is InAs single quantum well
- f = 500 nm



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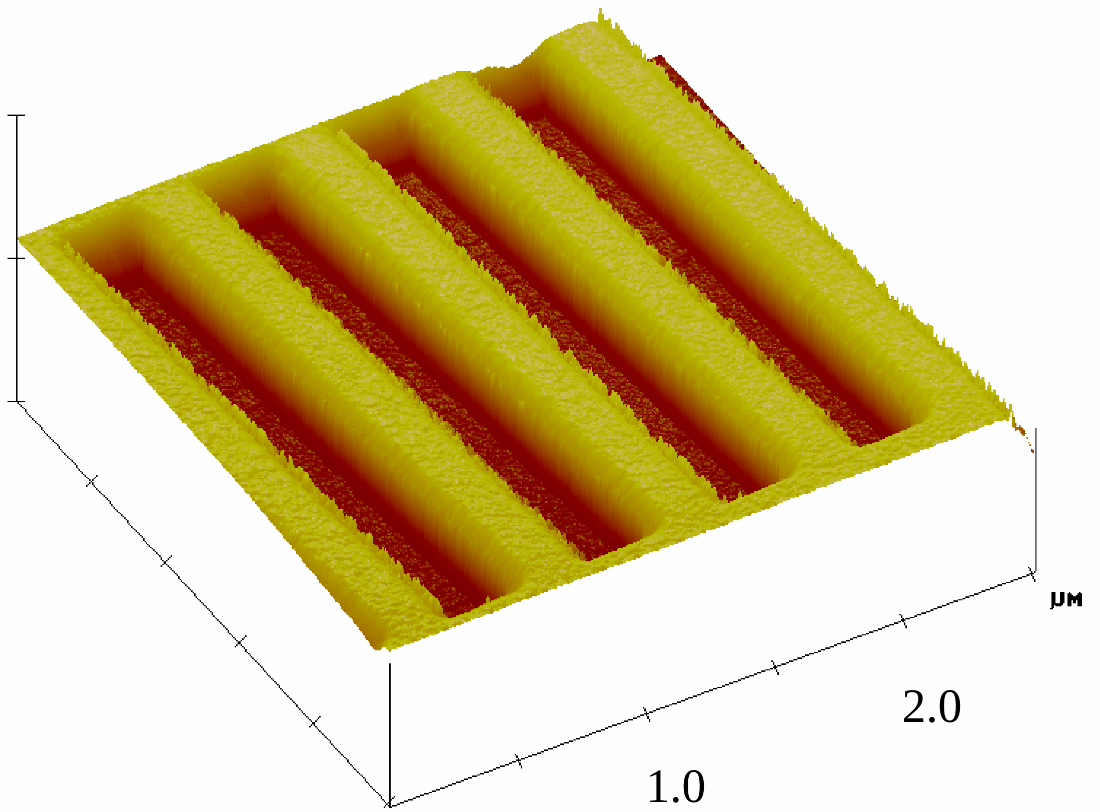
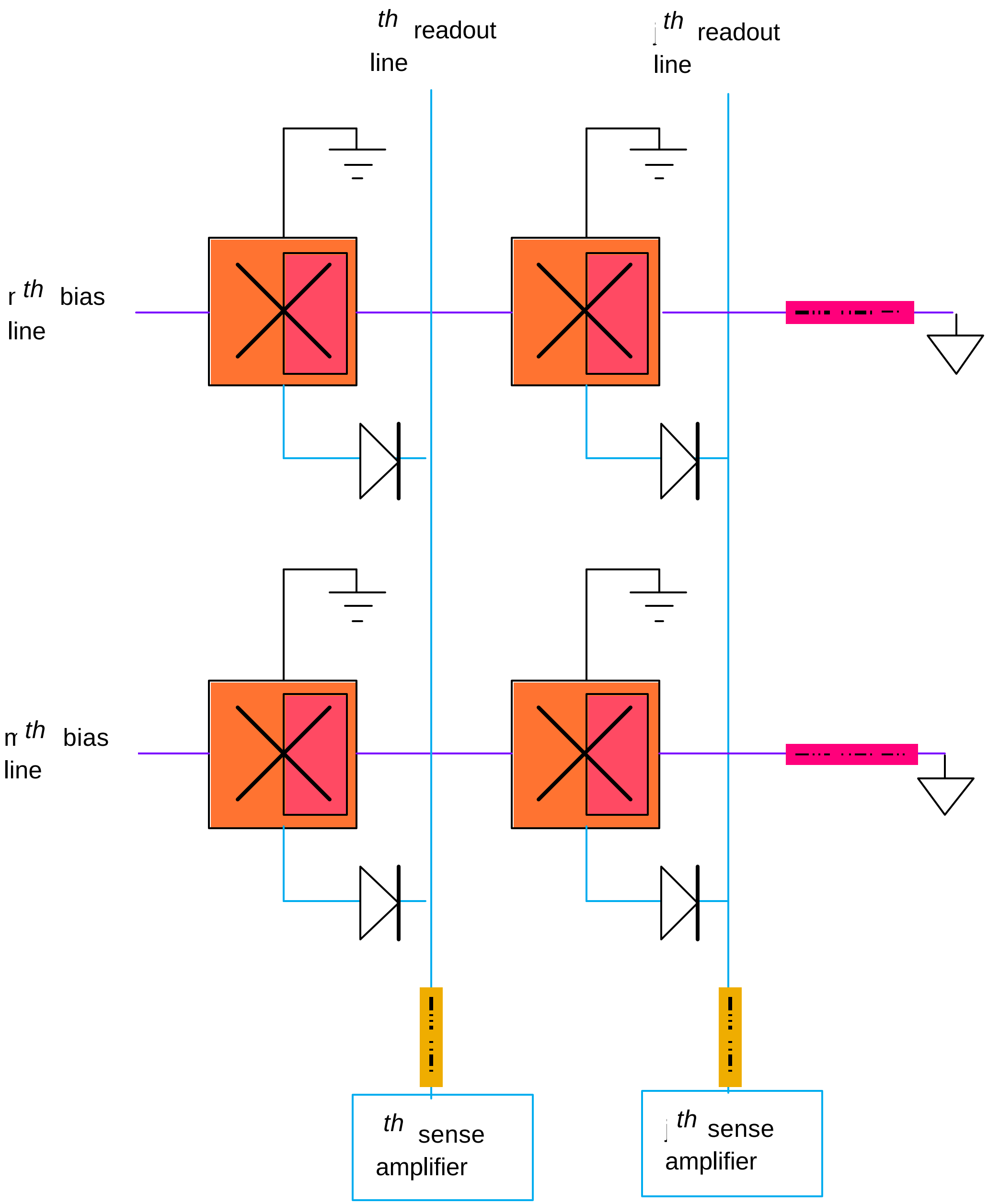
Developing e-beam lithography for nm scale Hall sensors

- Grating test structure, EBL and ion mill
- My approach:
  - Develop individual prototypes that are very sensitive
  - Optimize other characteristics for given need
  - Develop architecture (series or 2-dim arrays, etc.) for particular need



Memory Arrays
Sensor Arrays

- 2-dim array of memory cells, bit addressable
- Need isolation element in each cell
- Same architecture can be used for sensors, each cell is a “magnetic pixel”
- High sensitivity
- Relatively high circuit complexity



Summary

- Integrated sensors for localized magnetic fields
  - Magnetic tunnel junctions, spin valves, Hall effect
- Properties for consideration:
  - Sensitivity to relevant component of field (ideally, sense all components)
  - Insensitivity to externally applied field
  - Sensing at dc (rather than ac, lockin techniques) offers greatest flexibility
  - $dR/dB \,\big|_{B=0}$ large
  - Sensor should be close to surface
  - Surface should permit functionalization
  - Variety of architectures (meander line, 2-dim arrays)
  - Scalability: maintain sensitivity as f shrinks
  - Si (CMOS, SOI) or GaAs compatible